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RADIATION TRANSMISSION MEASUREMENTS FOR DEMRON FABRIC

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1.0 Background

Radiation Shield Technologies has requested a measurement survey of its Demron fabric to determine the shielding properties in the x-ray, gamma ray and beta particle emissions in the range of energies relevant to clinical and Homeland Security applications.

It is important to perform a detailed measurement program in order to sort out the shielding properties of this material in light of the often-times complex spectra emitted by standard radio-nuclides and x-ray generators. Low energy portions of the spectra are shielded more easily by this fabric than are the higher energy components and a simple single-layer test can lead to misleading results. This concept of "spectral hardening" was investigated by measuring the transmission factors for many layers and extracting information from the slopes of the transmission curves thereby obtaining a true picture of the shielding properties of the material as a function of energy.

After the initial measurement program was completed, the mass attenuation coefficients were calculated using the LLNL cross section data, TART code, RST supplied weight fractions and the measured density of the fabric. This code is used for the Monte Carlo simulation of coupled neutron-photon transport in 3-D geometry for shielding and other applications. With such a design tool, it is possible to "tune" the characteristics of the Demron fabric to meet the specific needs for a given radiation environment.

2.0 Facilities, sources and detectors

Several radio-nuclides were used for this study including ^{241}Am , ^{109}Cd , ^{137}Cs , ^{60}Co (gamma rays) and $^{90}\text{Sr}/^{90}\text{Y}$ (beta particle emission). These cover the energy from a few tens of keV to the MeV range. Transmission measurements using ^{241}Am and ^{109}Cd sources were made in a small calibration lab since the intensities were low while the ^{137}Cs , ^{60}Co and x-rays were measured in the LLNL radiation calibrations laboratory (B255, test cell A) since these sources were of high intensity. In all cases, the Demron fabric was placed about a meter from the high intensity sources and much closer for beta and low-intensity sources, and care was taken to eliminate secondary scattering processes.

The detector used for the ^{241}Am and ^{109}Cd sources was a Victoreen 471RF ion chamber, which has a flat energy response over the energy range of interest, while the detectors used for the ^{137}Cs and ^{60}Co sources were TLDs 700 (LiF). The reading from the ion chamber detector was read in real time whereas the TLDs were exposed for periods of tens of minutes and read off-line. In most cases, standard materials such as tantalum, lead, copper and aluminum were compared to the Demron fabric.

The transmission of x-ray intensity generated by 50 kV, 75 kV and 100 kV potential, reflected W target, was studied in the LLNL calibration facility (B255 test cell B) with currents in the 10 mA range and exposure times for the TLDs of tens of minutes. The output of the x-ray tube was filtered with a 4-mm -thick aluminum window to remove the very low portion of the x-ray spectrum.

3.0 Demron properties

Two samples of Demron fabric were supplied and appeared to be quite similar in both their physical characteristics and radiation shielding properties. The density was measured by weighing a large sample and calculating the volume by simple ruler and caliper measurements. The density of one sample was found to be 3.14 g/cm^3 , and the thickness was measured to be about 0.015 inch (0.38 mm) for a surface density of 0.12 g/cm^2 . The second sample was slightly lower density at 2.43 g/cm^3 , somewhat thicker - 0.02 inch (0.5 mm), but performed similarly. For the high energy gamma and the x-ray tests, we used only the higher density sample (0.38 mm thick) with many layers to obtain sufficient attenuation for a reliable measurement.

The fabric has the rubbery appearance of a piece of inner tubing from an automobile tire and has a cool feeling, a result of its high thermal conductivity. It is easy to handle and presents no toxic or disposal problems.

4.0 Gamma Ray measurements

4.1 Low energy, ^{241}Am : This radio-nuclide has a low energy component in the 10 – 20 keV range as well as a major component at 59 keV. The two-part transmission result is shown in Fig. 1 plotted as function of material thickness. For the low energy part of the spectrum with emission lines in the 13.9 to 20.8 keV range, a single layer of Demron reduces the transmission to 10% whereas for the higher energy spectrum at 59.54 keV, it takes approximately 0.3 to 0.4 cm or about 8 layers to reduce this emission line another factor of ten. The first layer of material removes the low energy spectrum leaving the higher energy portion for the remaining layers. This effect is recognized as "spectral hardening" and is well known in this field but can lead to misunderstanding in the data interpretation.

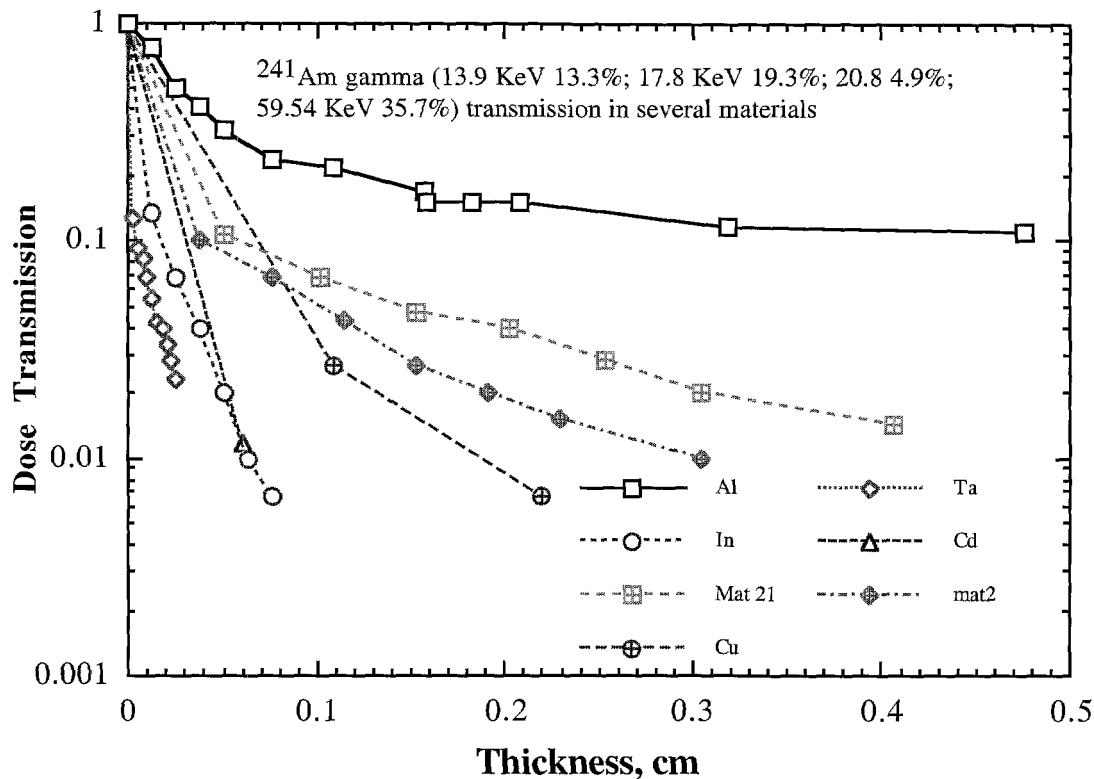


Figure 1. Transmission of ^{241}Am radiation dose through different materials. Results are plotted as a function of material thickness.

Plots of this type are often confusing because of the disparity of the densities of the materials, so for comparisons among many materials, it is useful to plot the transmission in terms of surface density per unit area (g/cm^2). Multiplying the thickness by the density (grams per square centimeter), the transmission information is expressed in Fig. 2.

In this measurement, the transmission, normalized to 100% for zero thickness of Demron is plotted as a function of Demron thickness expressed in terms of g/cm^2 . Each Demron data point corresponds to another single layer of material with the exception of the last data point that is a double thickness. Other standard materials are plotted for comparison. For a single layer, the fabric behaves similar to indium (initial slope) whereas at higher energies, i.e. multiple layers, the fabric behaves similar to tantalum. The single layer of fabric efficiently attenuates the low energy gamma rays, 10 – 20 keV, about a factor of ten. A single layer transmission of 10% (combined soft and hard), corresponds to a mass attenuation coefficient of about $19 \text{ cm}^2/\text{g}$ (low energy portion is $28 \text{ cm}^2/\text{g}$). This value is calculated by measuring the slope of the transmission curve to the first beak-point, i.e. the low energy portion. It is important to subtract the high energy component of this slope which is computed by examining the remainder of the data.

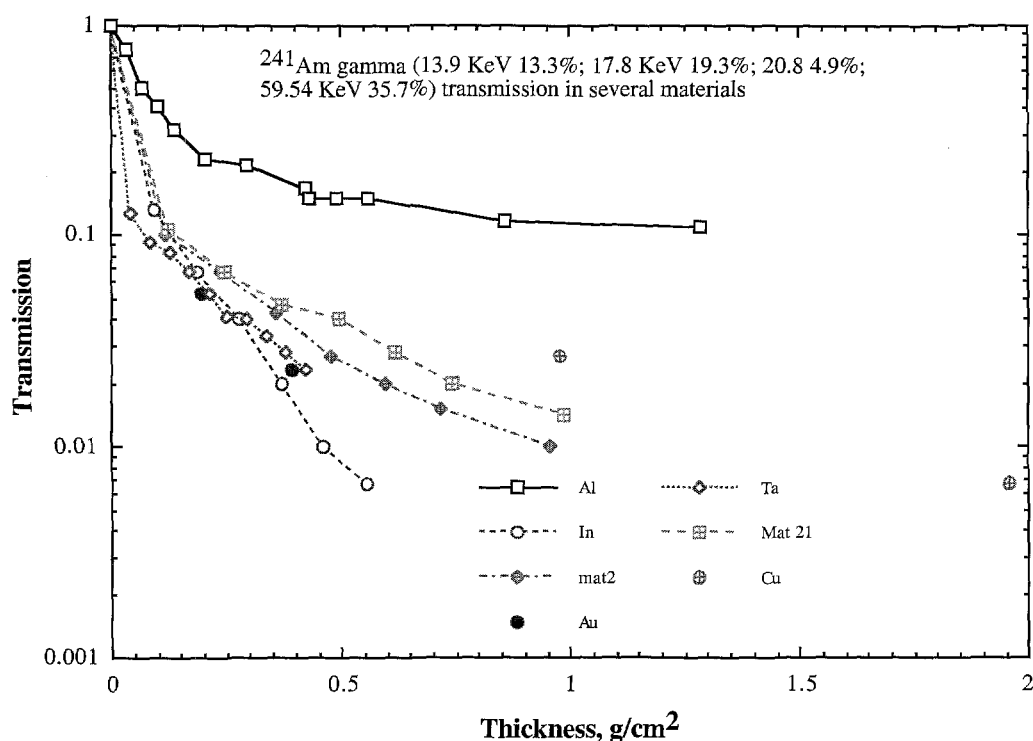


Figure 2. Transmission ^{241}Am radiation dose through different materials.
Results are plotted as a function of surface density.

Note that this coefficient is based upon the form for the transmission curve:

$$T = e^{-\mu_m t}$$

Where μ_m is the mass attenuation, in our case ambient dose attenuation, coefficient measured in cm^2/g and t is the thickness of the material as measured in g/cm^2 . In order to convert from this form of thickness to the actual material thickness, one divides by the material density. For example, in the above calculation, a thickness of $1/8.3 = 0.12 \text{ g}/\text{cm}^2$ will give a transmission of $10^{-1} = 10\%$ and this thickness corresponds to $0.12 \text{ g}/\text{cm}^2 / 3.14 \text{ g}/\text{cm}^3$ or about 0.38 mm which is close to a single layer thickness of Demron material.

For the low energy portion of ^{241}Am , $\mu_m = 28 \text{ cm}^2/\text{g}$ (after the slopes are separated). These mass attenuation coefficients will be tabulated later in this report.

After the single layer removes these low energy gammas, the remainder has a spectrum of about 59 keV and the mass attenuation coefficient drops to about 2.3 and 2.6 cm^2/g , respectively for the Demron materials. (This value is obtained by measuring the slope of the transmission curve from the first break-point out to the end of the curve and multiplying by $\ln 10 = 2.3$.)

Note also that the Demron material performs slightly worse than either indium or tantalum and although not tested in this series, lead, which is comparable to tantalum. In this low energy regime, where “edge” effects corresponding to inner shell electron absorption are present, exact equivalence is unclear because these edge effects, which represent sharp (i.e. narrow energy) absorptions, are energy dependent. This topic will be covered in more detail later in this report.

4.2. Low Energy, ^{109}Cd :

For ^{109}Cd , the low energy spectrum is also in the 20 keV range but the high energy line is at 88 keV. For this radio-nuclide, the data out to about 1 g/cm^2 show two slopes, as shown in Fig. 3.

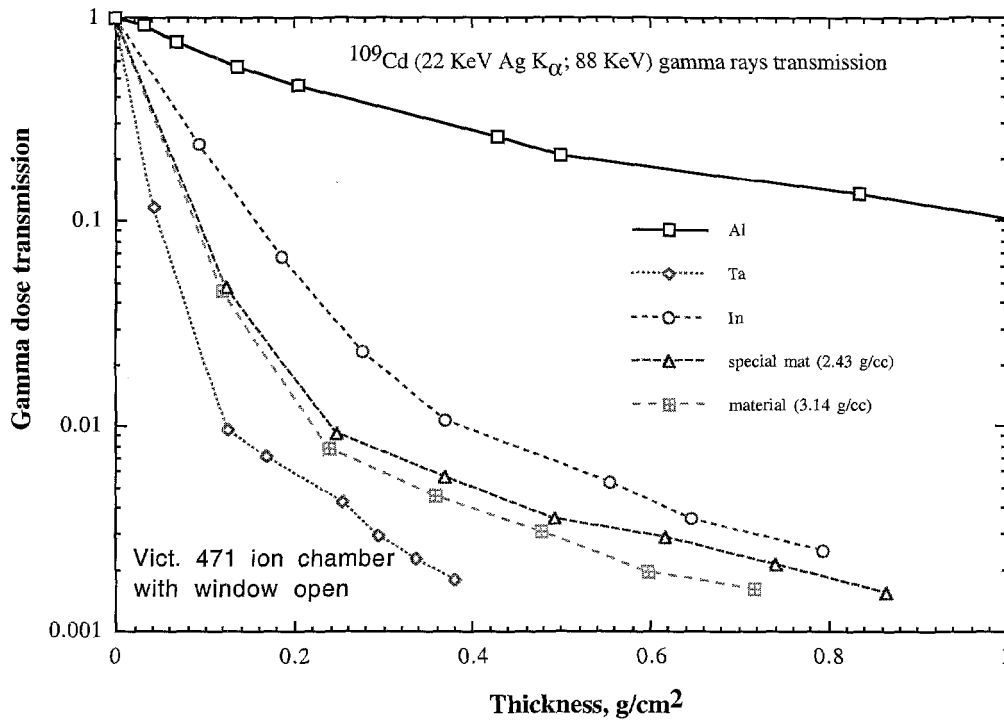


Figure 3. Transmission of ^{109}Cd gamma dose through different materials.

For this radio-nuclide there appear to be two slopes, the low energy transmission coefficient of $\mu_m = 27 \text{ cm}^2/\text{g}$ out to a thickness of about 0.12 g/cm^2 (single layer) and a high energy coefficient of $\mu_m = 3.4 \text{ cm}^2/\text{g}$ beyond 0.2 g/cm^2 thickness. These coefficients are in good agreement with the calculated results that will be shown in Fig. 8. Again, the Demron material performs comparably to both indium and tantalum, in this case, slightly better than indium and slightly worse than tantalum.

Thus for the moderate energy tail in the 88 keV range, the transmission coefficient is about 3 to 3.4 cm²/g corresponding to an order of magnitude decrease in transmission for every 6 layers of Demron, once the low energy gamma rays have been removed (essentially by a single layer of this material).

4.3 Moderate energy, ¹³⁷Cs:

For this radio-nuclide, the dominant emission is at 660 keV and the transmission curve indicates only a single slope as shown in Fig. 4. The mass attenuation coefficient is $\mu_m = 0.034 \times 2.3 = 0.08$ cm²/g corresponding to a Demron thickness of about 2.7 cm (or 72 layers) for a factor of two reduction in transmission. For a factor of 10 reduction in transmission, one would require 29 cm of Demron or 240 layers, at least for the present material. In this limited thickness and energy regime, the Demron appears to attenuate slightly better than tantalum, and lead should be similar to tantalum, expressed in mass per unit area.

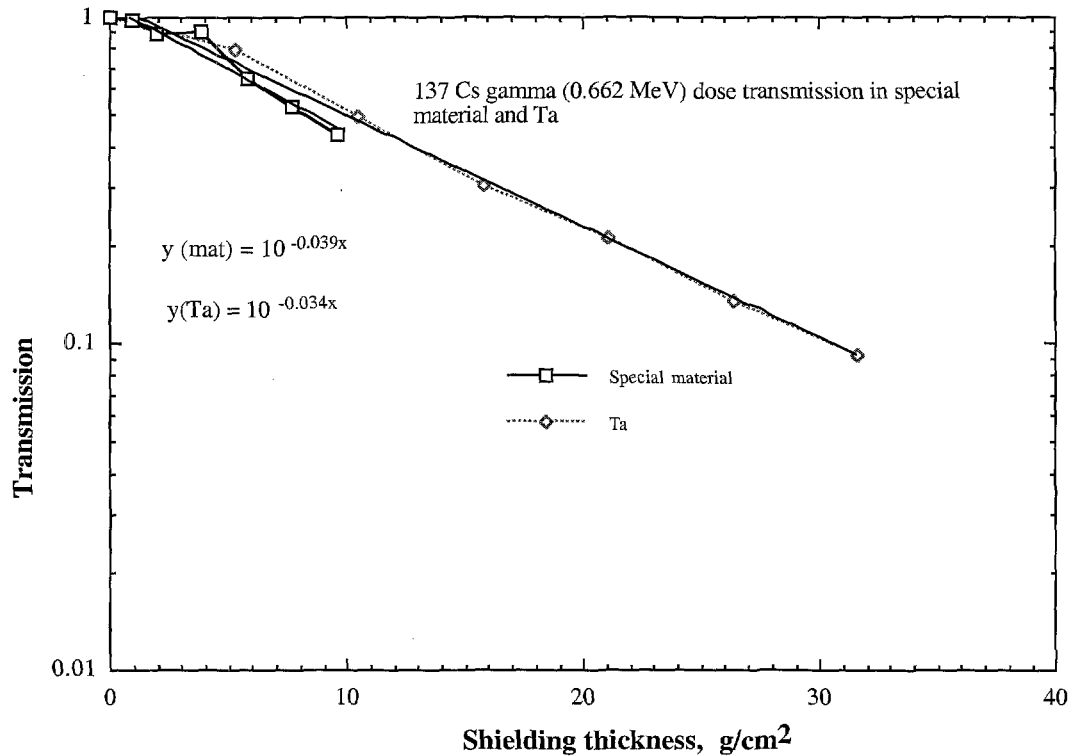


Figure 4. Transmission of ¹³⁷Cs gamma dose through the special material and Ta.

4.4 High energy gammas, ^{60}Co :

This radio-nuclide has two dominant emission lines, one at 1.17 MeV and the other at 1.33 MeV. The transmission curve, shown in Fig. 5 has a single slope corresponding to a mass attenuation coefficient of $\mu_m = 0.021 \times 2.3 = 0.05 \text{ cm}^2/\text{g}$, comparable to tantalum. For a factor of two reduction in transmission, the thickness of Demron required is about 4.4 cm or 115 layers, while for an order of magnitude decrease in transmission, almost 383 layers would be required.

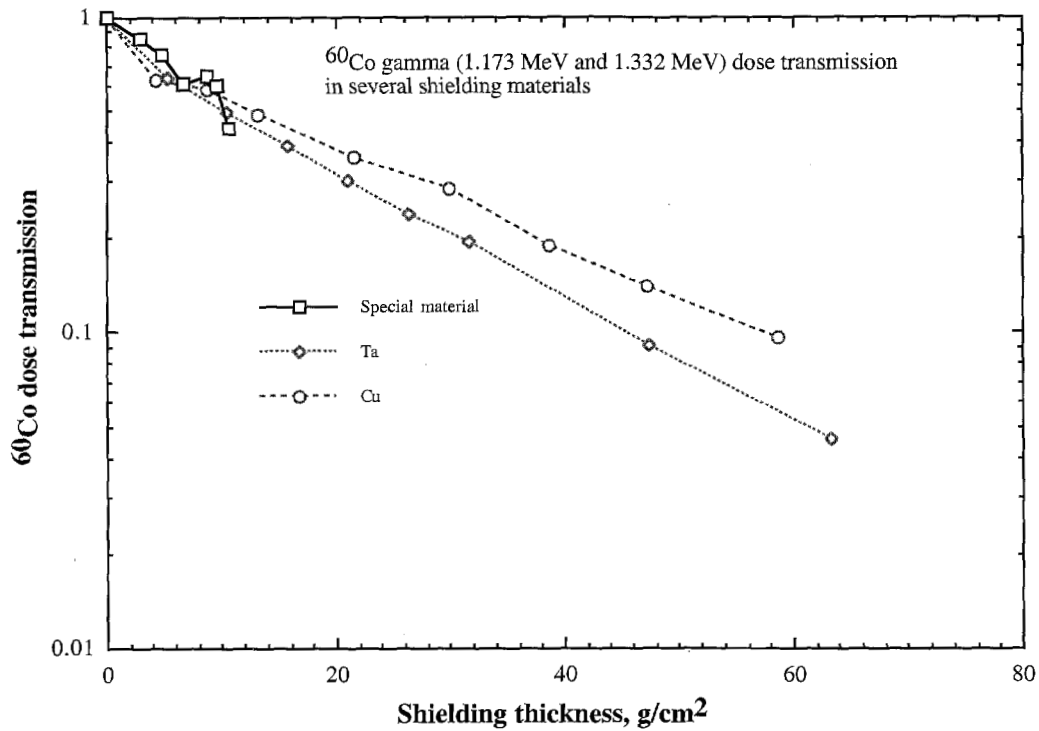


Figure 5. Transmission of ^{60}Co mono-energetic gammas dose through the special material and Ta and Cu.

5.0 X-ray measurements

Measurements of the mass attenuation coefficients for Demron for x-rays in the range 50 – 100 kV potential are shown in Fig. 6.

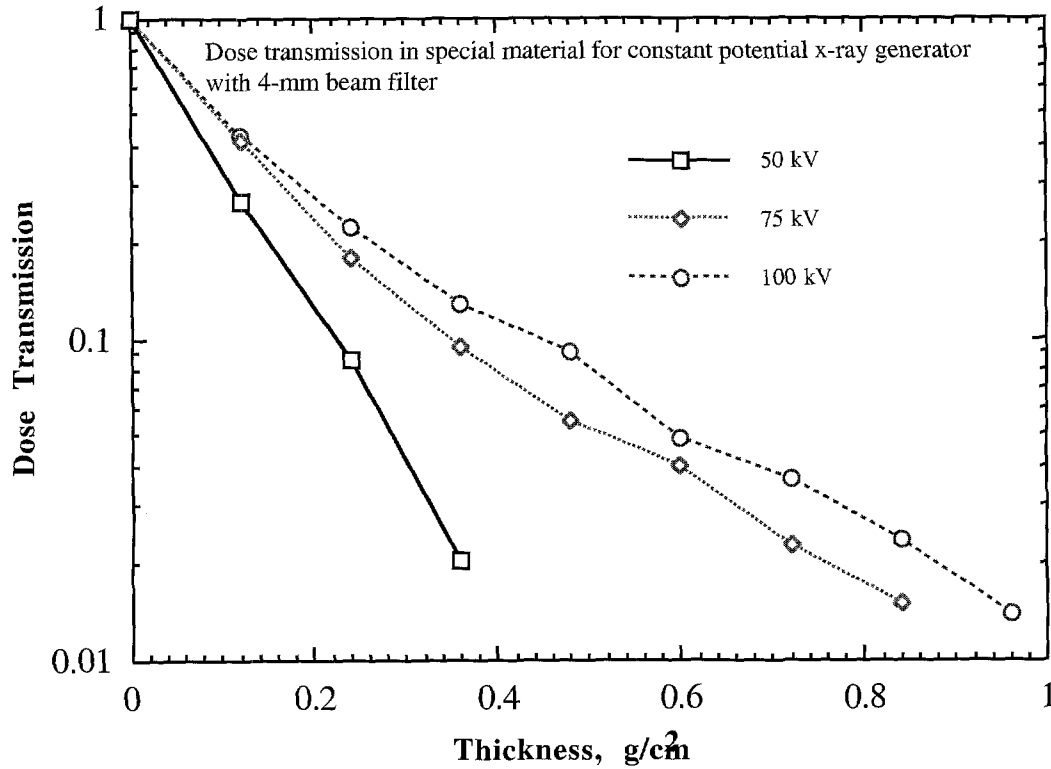


Figure 6. Transmission of x-rays dose through special material (Demron) for a constant potential x-ray generator with a 4-mm-thick aluminum beam filter

For the 50 kV potential, the mass attenuation coefficient $\mu_m = 4.5 \times 2.3 = 10.5 \text{ cm}^2/\text{g}$. For the 75 and 100 keV potentials, the slopes yield mass attenuation coefficients of $4.1 \text{ cm}^2/\text{g}$ for 75 keV and $3.8 \text{ cm}^2/\text{g}$ for 100 keV. In these last two measurements, the slopes were calculated by omitting the first two points which show slightly higher coefficients due to the presence of some low energy part of the spectrum.

6.0 Beta ray measurements

The Demron fabric and various other standard materials were exposed to a $^{90}\text{Sr}/^{90}\text{Y}$ beta emitter. The beta spectrum consists of 546 keV (Sr) and 2.27 MeV (Y) beta particles and the results are shown in Fig. 7. For the Demron material, the mass attenuation coefficient is $\mu_m = 8.0 \text{ cm}^2/\text{g}$ over the entire range of thickness measured. The material appears to be comparable to indium and a little worse than tantalum, again expressed in mass per unit area.

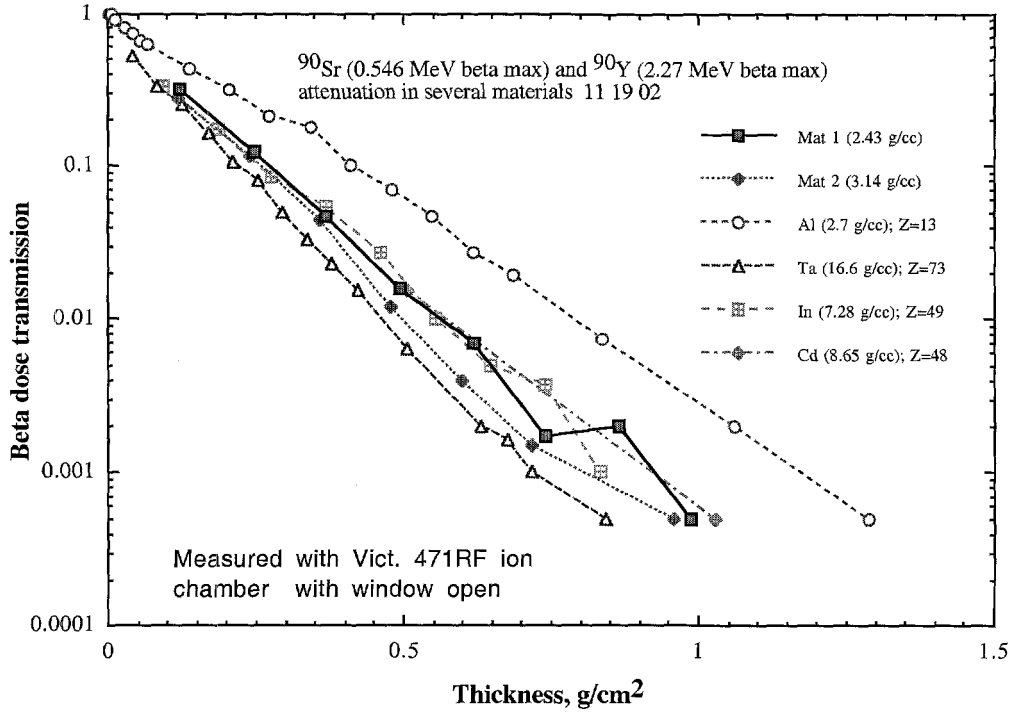


Figure 7. Transmission of beta radiation dose through several different materials.

7.0 Model calculations

The mass attenuation coefficients for two materials was calculated using the TART code, developed at LLNL for the purpose of radiation transport calculations. The code requires the weight fractions of all elements in a material sample. For the Demron material, the weight fractions specified by RST were used along with the final density as measured at LLNL. Tantalum was also modeled since this material was used as a comparison in all of the experiments. The code predictions are shown in Fig. 8 along with the coefficients based on our dose measurements.

In our shielding studies, photon energies of several keV to several MeV are important. For this energy regime, the photoelectric, Compton scattering, and pair production mechanisms of interaction predominate. In the photoelectric interaction, a photon interacts with an entire atom, resulting in the emission of a photoelectron, usually from the K and L shells of the atom. The difference in energy (binding and incoming photon) is carried by the outgoing photon and the emitted electron. The photoelectric cross section varies as Z^4/E^3 for energies up to about 150 keV. As the energy drops below the shell binding energy, the cross

section drops discontinuously and then rises with decreasing photon energy until it hits another edge, etc.

In Compton scattering, the electrons are assumed to be free. The Compton effect for an atom is the additive effect of all its electrons, and the cross section therefore is determined primarily by the electron density only. This process scales linearly with the number of electrons per atom.

In the process of pair production a photon interacts with the electric field of the atomic electrons or the nucleus. The photon is annihilated and its energy converted into the mass of an electron-positron pair. Threshold for pair production is 1.022 MeV. It is important at high energies and for high-Z materials.

The mass attenuation coefficient is sum of the cross section for these processes for the energy region of interest. The total mass attenuation coefficient is shown in Fig. 8.

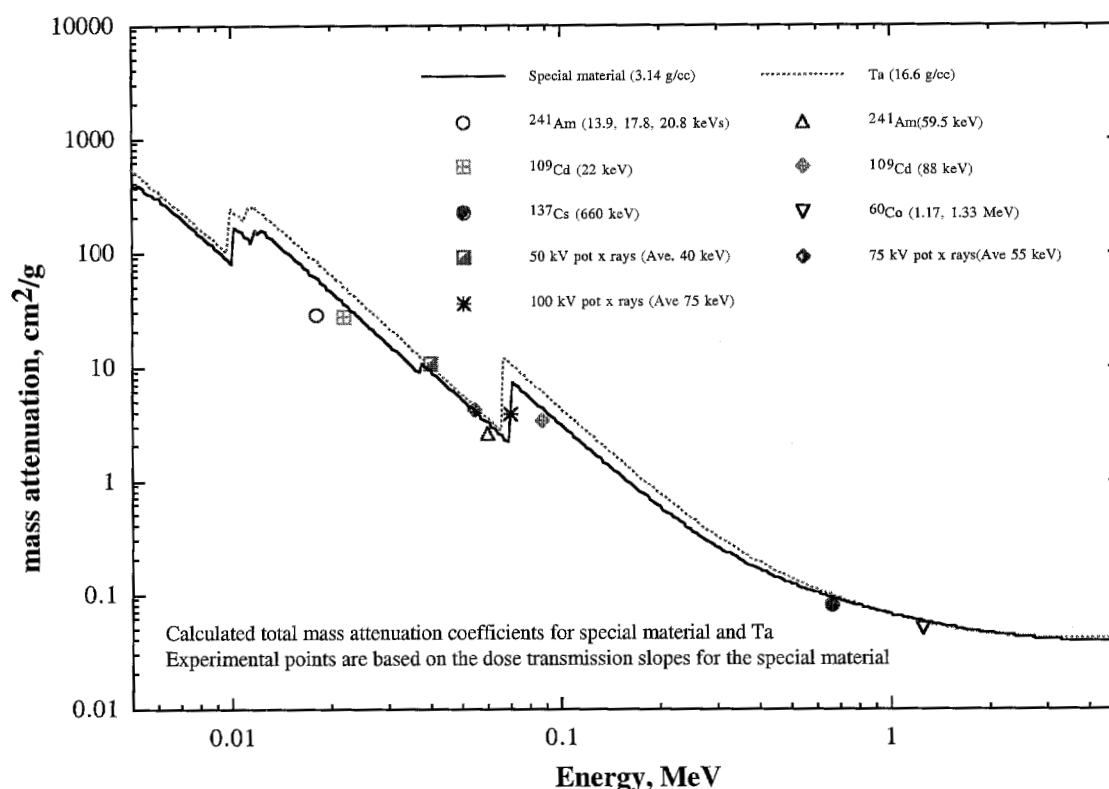


Figure 8. Mass attenuation coefficient predicted by TART code for Demron fabric and tantalum and the measured values.

The model shows the close comparison between Demron fabric and tantalum, a relationship which is borne out by the experimental data out to the megavolt range. Even the location of the K and L edges in the range below 100 keV matches closely due to the detailed characteristics of the Demron fabric.

8.0 Summary

Radiation testing on Demron fabric samples was performed by the US Department of Energy at Lawrence Livermore National Laboratory. Conclusions from those tests and calculations include:

- 1) Demron is effective as a radiation shield, comparable to lead in terms of g/cm^2 and tantalum according to the mass attenuation coefficient, against gamma, x-ray and beta emissions. For example, for 100 keV photon radiation, the mass attenuation coefficient is about $3.8 \text{ cm}^2/\text{g}$, which means that the transmission will be down to the $1/e$ point for a thickness of $1/3.8 = 0.26 \text{ g}/\text{cm}^2$. For Demron, with a density of $3.14 \text{ g}/\text{cm}^3$, the thickness would be 0.8 mm corresponding to 2 layers for the present sample. For lead with a density of $11.3 \text{ g}/\text{cm}^3$, the thickness would be 0.2 mm.
- 2) Demron's physical characteristics as a flexible, malleable fabric make it much easier to work with and handle than lead.
- 3) Demron feels cool to the touch.
- 4) Unlike lead, according to Radiation Shield Technologies, Demron is non-toxic, contains no dermal or inhalation risks to the user, and requires no special or restrictive conditions for disposal.
- 5) At the current sample thickness (0.38 mm), Demron provides a factor 3 protection against beta and a factor of 10 against low energy gamma emissions.
- 6) The mass attenuation coefficients can be used to determine the thickness of Demron fabric required to successfully shield against higher energy/intensity gamma radiation.

While the exact composition and construction of the Demron fabric is proprietary, it can be concluded that for radiation shielding purposes, Demron shields similar to lead by weight, yet poses none of lead's environmental or biological dangers.